

Process for producing monolithic oxidation catalysts
and their use in the gas-phase oxidation of
hydrocarbons

5 The invention relates to a process for
producing monolithic oxidation catalysts and to their
use in the gas-phase oxidation of hydrocarbons.

Supported catalysts for the gas-phase oxidation
of hydrocarbons to give the corresponding oxidation
10 products such as carboxylic acids, carboxylic
anhydrides or aldehydes, which catalysts have a
catalytically active surface coating consisting
essentially of titanium dioxide (TiO_2) and divanadium
pentoxide (V_2O_5), have been known for a long time. A
15 typical example of the use of such catalysts is the
preparation of phthalic anhydride, in which mixtures of
o-xylene and air or naphthalene and air or o-xylene,
naphthalene and air are passed over an appropriate
catalyst in a shell-and-tube reactor. The heat
20 generated in this strongly exothermic reaction is
customarily removed (cooling, isothermal reaction
conditions) by means of a salt melt which surrounds the
reaction tubes.

The supported catalysts used here comprise an
25 inert support body, for example having a ring shape or
a spherical shape, on which the actual catalytically
active composition is present. The active composition
consists predominantly of the main components TiO_2 in
the anatase form and V_2O_5 . To improve the control of the
30 activity and to improve the selectivity, further
activating or deactivating additives, for example
oxides of transition elements or alkali metal
compounds, are frequently added in small amounts as
dopants (promoters) to the catalytically active
35 composition.

The supported catalysts are generally produced
by spraying aqueous suspensions or aqueous solutions of
 TiO_2 and V_2O_5 , frequently with addition of promoters and

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possibly binders for improving adhesion of the active components to the support, onto the support bodies.

As support bodies, use is made of regularly shaped, mechanically stable bodies such as spheres, rings, half rings, saddles, etc., particularly preferably rings or spheres. The size of the support bodies is determined predominantly by the dimensions of the reactor, especially by the internal diameter of the reaction tubes.

Support materials used are, for example, steatite, Duranit, earthenware, silicon dioxide, silicon carbide, aluminates, metals and metal alloys.

EP-A 744214 (US-A 5792719) discloses a procedure for producing catalysts in which TiO_2 , V_2O_5 , SiC and possibly dopants such as CsCO_3 and $(\text{NH}_4)_2\text{HPO}_4$ are stirred in aqueous suspension for a number of hours, and the suspension is subsequently admixed with an organic binder. This suspension is sprayed onto the support material and the supported catalyst is dried.

In industry, it is customary for each of the reaction tubes to be filled with various catalysts which have different catalytically active compositions. These can be arranged, for example, in two superposed zones, an upper zone and a lower zone. This measure makes it possible to match the activity of the catalyst system in the reactor appropriately to the course of the reaction.

During the reaction, the major part of hydrocarbon is reacted in the upper part of the reaction tube. As a result, the highest temperatures inevitably also occur there. In the lower part of the tube, only a sort of after-reaction takes place. There, remaining o-xylene/naphthalene and intermediates, for example o-tolualdehyde and phthalide, are converted into phthalic anhydride. Furthermore, by-products such as quinones are also oxidized further.

As a result of aging processes, all catalysts lose activity as the time for which they have been used

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increases. This occurs predominantly in the main reaction zone, since this is where the catalyst is subject to the highest temperatures. During the life of the catalyst, the main reaction zone migrates ever
5 further into the catalyst bed. This steadily decreases the length of the remaining catalyst bed and adversely affects the after-reaction. As a consequence, intermediates and by-products can no longer be reacted completely and the product quality of the phthalic
10 anhydride produced therefore deteriorates to an increasing extent. An aging process is particularly critical in the case of high feed loadings. Although the fall-off in the reaction and thus the deterioration in product quality can be countered by increasing the
15 reaction temperature, for example by means of the salt bath temperature, but only to a temperature of about 400°C, this temperature increase is always associated with a loss in yield.

DE-A 1793267 (GB-A 1274471) describes a process
20 for preparing phthalic anhydride, in which the overall oxidative reaction is divided in process engineering terms into two parts. The reaction is controlled so that the reaction conditions in the second part, known as the after-reaction, are significantly more
25 aggressive than in the first part. This can be achieved, for example, by carrying out the after-reaction without cooling, i.e. adiabatically. This after-reaction can be carried out in a separate reactor having different tube dimensions or even in a
30 downstream shaft oven.

DE-A 2005969 describes a process for preparing phthalic anhydride, in which from about 80 to 99% of the total feed is reacted isothermally, i.e. cooled, in the main reaction. Conversion of the remaining
35 unreacted feed occurs in a downstream adiabatic reactor. In addition, in the reaction procedure described, the gas mixture leaving the isothermal reactor is cooled further before it enters the

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downstream adiabatic reactor. This process variant is likewise intended to enable the phthalic anhydride formed to be obtained largely free of by-products and without a loss in yield. Here too, a shaft oven is
5 claimed as adiabatic reactor.

AT-A 9201926 describes a process for preparing phthalic anhydride in a main reactor having a downstream adiabatic reaction zone. Here, it is expressly stated that, for economic reasons, it is
10 advantageous for the adiabatic reactor to be connected directly to the main reactor. Apart from the use of catalyst base bodies in the form of rings or spheres, mention is also made of the possible use of a catalyst
15 having a monolithic structure, for example in the form of a honeycomb. In the reaction procedure described, this measure enables the yield of phthalic anhydride to be increased by about 1% by weight. The formation of the by-product phthalide is at the same time significantly reduced. The use of the monolithic
20 catalyst shape mentioned is not described in any example. Likewise, no details are given of the production of a monolithic catalyst and associated problems.

Owing to the laminar flow occurring in
25 honeycomb catalysts, they have only a very low pressure drop even at very high gas velocities. However, a disadvantage is that, owing to the lack of turbulent flow resulting from the shape, heat and mass transfer in the honeycomb channels, and thus heat removal, are
30 greatly reduced. This situation makes use of honeycomb catalysts as catalyst supports virtually impossible for strongly exothermic processes in conjunction with a selective oxidation. Honeycomb catalysts have therefore become established industrially only in waste gas
35 purification or waste gas incineration where all the organic constituents undergo total oxidation to CO_2 .

Coating monolithic support material with a catalytically active composition comprising the main

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constituents TiO_2 , V_2O_5 and possibly dopants by generally known methods, for example a dipping process, is found to be impractical. This is because coating suspensions based on commercially available TiO_2 have a very high viscosity even at solids concentrations of 30-35% by weight and thus make coating of the channels of a monolithic support material virtually impossible without blocking the channels.

In order to coat monolithic catalyst supports with the necessary amount of catalytically active composition, for example 50-150 g of active composition per liter of catalyst, the coating process would have to be carried out with such a low-concentration "active composition" suspension that the necessary layer thickness would be achieved only after repeating the coating process a number of times. However, this at the same time once again increases the problem of blocking of the channels in the catalyst support because of the multiple coating steps. Furthermore, this is associated with significantly more work and thus with increased costs and is therefore uneconomical.

It is therefore an object of the invention to provide a simple and preferably single-stage process for producing monolithic catalysts based on TiO_2 /metal oxides.

It has now surprisingly been found that the viscosity of highly concentrated TiO_2 coating suspensions having a high solids content can be greatly reduced by addition of surfactants.

The invention provides a process for producing monolithic supported catalysts for gas-phase oxidation by coating the catalyst support by means of a suspension, wherein the latter comprises catalytically active composition and one or more surfactants of the formula



where R is the hydrophobic part(s) of the surfactant and n is 1, 2 or 3; Y is the hydrophilic part of the surfactant and m is 0, 1, 2 or 3, and X is the hydrophilic head group of the surfactant.

5 The viscosity of highly concentrated TiO_2 coating suspensions having a solids content of greater than 30% by weight can be greatly reduced by addition of from 1 to 10% by weight, preferably from 2 to 5% by weight, of surfactants of the formula R_nY_mX .

10 In this formula, R is one or more hydrophobic parts, for example alkyl, aryl and alkylaryl groups, of a surfactant, where n is 1, 2 or 3, preferably 1 or 2. Y is the hydrophilic part of a surfactant, where m is 0, 1, 2 or 3, preferably from 0 to 2. X is the
15 hydrophilic head group of the surfactant.

 Preference is given to surfactants having head groups X selected from among phosphates, phosphonates, sulfates, sulfonates and carboxylates, dicarboxylates (malonic acid derivatives, succinic acid derivatives,
20 adipic acid derivatives, maleic acid derivatives, phthalic acid derivatives) and polycarboxylates, for example polyacrylates, polymethacrylates or polymaleic acid derivatives substituted by surfactant radicals (R,Y).

25 In these head groups X, some of the acid radicals may be present in the H form as free acid groups, in the form of an ammonium salt or as a metal salt. Particular preference is given to free acid groups, ammonium salts and alkaline earth metal salts.

30 The hydrophilic group Y can be bound to the central atom of the head group X either directly or via an oxygen. Preferred central atoms are carbon, phosphorus and sulfur.

 The hydrophobic groups R are preferably bound
35 to the head group via a hydrophilic group Y.

 Preferred embodiments of the hydrophobic parts R are alkyl radicals having relatively long-chain carbon building blocks with from 5 to 30 carbon atoms,

preferably from 10 to 20 carbon atoms. The alkyl radicals can be saturated or unsaturated or branched carbon chains. The alkyl radicals can be bound directly or via aryl groups to the hydrophilic part Y or the
5 head group X.

The hydrophilic radical Y generally comprises polymeric alkoxy units, preferably propoxy, ethoxy or methoxy units, with the degree of polymerization being able to be from 1 to 50 monomer units, preferably from 5 to 20
10 monomer units.

The coating suspension used according to the invention can comprise, for example, surfactants of the formula R_nY_mX selected from the group consisting of calcium alkylarylsulfonates, ammonium alkylaryl-
15 sulfonates, calcium dodecylbenzenesulfonate, polyethoxy(dinonyl phenyl ether phosphate), polyoxoethylene(lauryl ether phosphate), polyethoxy-(tridecyl ether phosphate), calcium dodecylbenzenesulfonate, tridecyl phosphate esters,
20 ethoxylated phosphated alcohols, alkyl polyoxyethylene ether phosphate, ammonium nonyl phenyl ether sulfate.

The surfactants can be used without addition of further surfactants or together with other surfactants, for example alkylphenol ethoxylate.

25 The addition according to the invention of the surfactants to the coating suspension allows low-viscosity coating suspensions having high solids contents of TiO_2 and/or V_2O_5 to be prepared and to be used for coating monolithic support material, for
30 example honeycombs and supports having open or closed cross-channel structures. The coating suspensions may further comprise other additives, for example SiC. The solids contents of catalytically active composition in such suspensions can be set to values of up to 50% by
35 weight and above. Such highly concentrated suspensions allow monolithic and, in particular, honeycomb catalyst supports coated with from 50 to 150 g of active

composition per liter of honeycomb catalyst to be obtained without problems in one coating step.

Suspensions having a solids content of TiO_2 of greater than 35% by weight have, owing to the high viscosity, greatly reduced flow and can therefore no longer flow through narrow channels. Changing to larger particle sizes does not lead to success either. The addition of one or more of the surfactants claimed significantly improves flow.

The catalysts of the invention can be produced using uniform TiO_2 grades or mixtures of various TiO_2 grades, which may in turn be doped or coated with metal oxides. The active composition preferably comprises V_2O_5 as additional component.

The coating of honeycombs with coating suspensions without addition of surfactants can be carried out without problems only using suspensions having a relatively low solids content of about 30% by weight. However, the amounts of active composition which can be applied in this way are only about 20 g/l of catalyst. If the solids content is slightly increased, the viscosity of the suspension increases so much that the suspension can no longer flow out of the honeycomb channels and blocking of the channels therefore results.

The use of the surfactants claimed enables the honeycombs to be coated without problems even using suspensions containing more than 50% by weight of active composition.

Applied amounts of over 100 g of solid/l of honeycomb catalyst can be achieved without problems in one coating step when using the surfactants claimed.

Examples of support materials suitable for coating by the process of the invention are materials such as cordierite, silicates, silicon dioxide, silicon carbide, aluminum oxide, aluminates or mixtures of these materials and metals or metal alloys. The support bodies can also have closed or open cross-channel

structures. The suspensions used according to the invention enable honeycombs having a high to very high cell density to be coated without the danger of blocking the channels.

- 5 Preference is given to honeycombs having a cell density, i.e. a number of channels, of from 100 to 400 csi (cells per square inch), particularly preferably from 100 to 200 csi.

10 Monolithic catalysts are very well suited to the selective oxidation of o-xylene/air mixtures having low o-xylene contents to give PA. The monolithic catalysts do not in any event have a tendency to produce a runaway reaction. Surprisingly, the monolithic catalysts are superior to the conventional
15 ring catalyst (for the same active composition).

Catalysts produced according to the invention and having a content of active composition of from 40 to 200 g per liter of catalyst are particularly advantageous. At a comparable temperature, these
20 achieve higher conversions, better PA selectivities and smaller amounts of by-products.

The honeycomb catalysts produced according to the invention are very useful as catalysts for an after-reaction of a PA process gas comprising one or
25 more of the starting materials o-xylene and naphthalene and/or intermediates such as tolualdehyde, phthalide, naphthoquinone, etc. This reaction is advantageously carried out at lower gas inlet temperatures, based on the temperature of the main reactor. In this after-
30 reaction, a major part of the underoxidation products can be removed from the reaction gas and reacted further to form PA. Surprisingly, this also occurs at relatively high space velocities of 20,000-30,000 h⁻¹. Even in the presence of relatively high contents of
35 underoxidation products together with a high concentration of PA, no runaway reaction occurs when using the catalysts of the invention.

The monolithic catalysts produced according to the invention are particularly suitable for preparing phthalic anhydride in an adiabatic reactor (after-reactor) in combination with an isothermally operated reactor (main reactor, for example filled with a bed of particulate catalyst).

The adiabatic reactor can also be operated advantageously with upstream gas cooling. In a particularly preferred embodiment, the upstream gas cooling and the adiabatic reaction are carried out in a joint apparatus.

In industry, it is customary to cool the reaction gas in a gas cooler before isolation of the product. The upstream gas cooling, the adiabatic reaction in the monolithic catalyst bed and further cooling can be carried out within the reactor or outside the reactor, or in a joint apparatus.

Detailed description of the invention
The invention is illustrated in more detail by the following examples.

The following examples demonstrate the influence of surfactants from the group consisting of phosphoric esters on the viscosity of support oxide suspensions. The flow behavior of the suspensions prepared was determined by a method based on DIN 53211 using a flow cup. Two types of TiO_2 which differed from one another only in the particle size were tested. The mean particle diameter was 0.1 and 0.4 μm , respectively. This measurement method was selected since it could appropriately simulate flow of a suspension out of the honeycomb channels. As outflow nozzle, use was made of a nozzle having a diameter of 2 mm corresponding to a flow orifice area of 3.14 mm^2 . For comparison, a 200 csi honeycomb has a channel cross section of 2.3 mm^2 and a 100 csi honeycomb has a channel cross section of 4.66 mm^2 . If the viscosity of the suspension was too high, i.e. the suspension could not flow through the nozzle under these conditions, the experiment was repeated using a nozzle opening of 4 mm

diameter. If no outflow of the suspension could be measured even under the altered conditions, the experiment was evaluated as "not measurable".

5 **Comparative Example 1 (30% strength by weight suspension without surfactant):**

 A suspension was prepared from a mixture of 30 g of TiO_2 having a mean particle diameter of $0.1 \mu\text{m}$ and 70 g of water and was stirred for 2 hours. The flow
10 was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 1.4 ml/sec.

Comparative Example 2 (33% strength by weight suspension without surfactant):

15 A suspension was prepared from a mixture of 33 g of TiO_2 having a mean particle diameter of $0.1 \mu\text{m}$ and 67 g of water and was stirred for 2 hours. The flow was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, no outflow was observed. At a nozzle
20 diameter of 4 mm, the outflow rate was 6.2 ml/sec.

Comparative Example 3 (22% strength by weight suspension without surfactant):

 A suspension was prepared from a mixture of
25 22 g of TiO_2 having a mean particle diameter of $0.4 \mu\text{m}$ and 78 g of water and was stirred for 2 hours. The flow was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 1.7 ml/sec.

30 **Comparative Example 4 (25% strength by weight suspension without surfactant):**

 A suspension was prepared from a mixture of
 25 g of TiO_2 having a mean particle diameter of $0.4 \mu\text{m}$ and 75 g of water and was stirred for 2 hours. The flow
35 was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, no outflow was observed. At a nozzle diameter of 4 mm, the outflow rate was 8.3 ml/sec.

Example 5 (45% strength by weight suspension):

A suspension was prepared from a mixture of 45 g of TiO_2 having a mean particle diameter of 0.1 μm , 55 g of water and 3.5 g of alkyl($\text{C}_8\text{-C}_{10}$)polyoxyethylene ether phosphate and was stirred for 2 hours. The flow was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 0.9 ml/sec.

Example 6 (45% strength by weight suspension):

A suspension was prepared from a mixture of 45 g of TiO_2 having a mean particle diameter of 0.4 μm , 55 g of water and 3.0 g of alkyl($\text{C}_8\text{-C}_{10}$)polyoxyethylene ether phosphate and was stirred for 2 hours. The flow was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 2.0 ml/sec.

Example 7 (45% strength by weight suspension):

A suspension was prepared from a mixture of 45 g of TiO_2 having a mean particle diameter of 0.4 μm , 55 g of water and 5.0 g of polyethoxydinonylphenyl ether phosphate and was stirred for 2 hours. The flow was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 1.2 ml/sec.

Example 8 (45% strength by weight suspension):

A suspension was prepared from a mixture of 45 g of TiO_2 having a mean particle diameter of 0.4 μm , 55 g of water and 2.0 g of a mixture of alkylphenol ethoxylate/calcium alkylarylsulfonate and was stirred for 2 hours. The flow was subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 1.3 ml/sec.

Example 9 (45% strength by weight suspension):

A suspension was prepared from a mixture of 45 g of TiO_2 having a mean particle diameter of 0.1 μm , 55 g of water and 5.0 g of calcium dodecylbenzenesulfonate and was stirred for 2 hours. The flow was

subsequently measured in the flow cup. At a nozzle diameter of 2 mm, the outflow rate was 0.5 ml/sec.

Example 10 (45% strength by weight suspension):

5 A suspension was prepared from a mixture of
45 g of TiO_2 having a mean particle diameter of $0.4 \mu\text{m}$,
55 g of water and 2.5 g of ammonium nonyl phenyl ether
sulfate and was stirred for 2 hours. The flow was
subsequently measured in the flow cup. At a nozzle
10 diameter of 2 mm, the outflow rate was 1.8 ml/sec.

Comparative Example 11:

 A suspension was prepared from a mixture of
38 g of TiO_2 having a mean particle diameter of $0.4 \mu\text{m}$,
15 9.5 g of V_2O_5 and 46.8 g of water and was stirred for
2 hours. The flow was subsequently measured in the flow
cup. The outflow rate could be measured neither using a
2 mm nozzle opening nor a 4 mm nozzle opening, since
the viscosity of the suspension was too high in both
20 cases.

Example 12:

 A suspension was prepared from a mixture of
38 g of TiO_2 having a mean particle diameter of $0.4 \mu\text{m}$,
25 9.5 g of V_2O_5 , 46.8 g of water and 3 g of
alkyl($\text{C}_8\text{-C}_{10}$)polyoxyethylene ether phosphate and was
stirred for 2 hours. The flow was subsequently measured
in the flow cup. At a nozzle diameter of 2 mm, the
outflow rate was 1.3 ml/sec.

30 Examples 13 to 17 below demonstrate the
production of catalysts by way of coating experiments
on appropriate monolithic support bodies.

**Comparative Example 13 (without addition of
35 surfactant):**

 354 g of TiO_2 (BET about $30 \text{ m}^2/\text{g}$) having a mean
particle diameter of $0.1 \mu\text{m}$, 118 g of TiO_2
(BET $< 10 \text{ m}^2/\text{g}$) having a mean particle diameter of

0.4 μm , 120 g of V_2O_5 and 8.24 g of $(\text{NH}_4)_2\text{HPO}_4$ were suspended in 1400 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. The solids content of the suspension obtained was 29.6% by weight.

5 60 g of organic binder, namely a copolymer of vinyl acetate and vinyl laurate, in the form of a 50% strength by weight aqueous dispersion were then added. A monolithic ceramic support honeycomb made of cordierite and having a cell density of 200 cpsi and

10 dimensions of 7.5 cm \times 7.5 cm \times 15 cm was then dipped into this coating suspension and taken from the dipping bath after about 1 minute. The residues of suspension present in the channels were blown out using an air blower (at not more than 130°C). Complete drying of the

15 coated honeycomb was carried out in a drying oven at 130°C for 12 hours. The amount of active composition applied was 20 g/l of catalyst. The honeycomb was just able to be coated.

20 **Comparative Example 14 (without addition of surfactant):**

To produce a catalyst coated with a larger amount of active composition, 354 g of TiO_2 (BET about 30 cm^2/g) having a mean particle diameter of 0.1 μm ,

25 118 g of TiO_2 (BET < 10 m^2/g) having a mean particle diameter of 0.4 μm , 120 g of V_2O_5 and 8.24 g of $(\text{NH}_4)_2\text{HPO}_4$ were suspended in 1220 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. The solids content of the suspension

30 obtained was 32.7% by weight. 60 g of organic binder, namely a copolymer of vinyl acetate and vinyl laurate, in the form of a 50% strength by weight aqueous dispersion were then added. Using this coating suspension, a monolithic ceramic support honeycomb made

35 of cordierite and having a cell density of 200 cpsi and dimensions of 7.5 cm \times 7.5 cm \times 15 cm was coated using a method analogous to Example 15. In this example, the suspension was so highly viscous that the channels

could not be freed completely of excess suspension even with the aid of the blower. About 10% of the channels remained blocked. The coated honeycomb could not be used as a catalyst.

5

Comparative Example 15 (Coating of rings):

To produce a ring-shaped comparative catalyst, 73.7 g of TiO_2 (BET about $30 \text{ m}^2/\text{g}$) having a mean particle diameter of $0.1 \mu\text{m}$, 24.6 g of TiO_2 (BET $< 10 \text{ m}^2/\text{g}$) having a mean particle diameter of $0.4 \mu\text{m}$, 25 g of V_2O_5 and 1.7 g of $(\text{NH}_4)_2\text{HPO}_4$ were suspended in 400 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. 6.2 g of organic binder, namely a copolymer of vinyl acetate and vinyl laurate, in the form of a 50% strength by weight aqueous dispersion were then added. All of this coating suspension was applied to 1225 g of steatite rings ($7 \times 7 \times 4 \text{ mm}$) as support material with evaporation of the water. The layer thickness of active composition was about $60 \mu\text{m}$.

Example 16 (Catalyst 1 according to the invention):

602 g of TiO_2 (BET about $30 \text{ m}^2/\text{g}$) having a mean particle diameter of $0.1 \mu\text{m}$, 200 g of TiO_2 (BET $< 10 \text{ m}^2/\text{g}$) having a mean particle diameter of $0.4 \mu\text{m}$, 204 g of V_2O_5 and 70 g of alkyl($\text{C}_8\text{-C}_{10}$)polyoxyethylene ether phosphate were suspended in 980 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. The solids content of the suspension obtained was 51% by weight. 60 g of organic binder, namely a copolymer of vinyl acetate and vinyl laurate, in the form of a 50% strength by weight aqueous dispersion were then added. Using this coating suspension, a monolithic ceramic support honeycomb made of cordierite and having a cell density of 200 cpsi and dimensions of $7.5 \text{ cm} \times 7.5 \text{ cm} \times 15 \text{ cm}$ was coated using a method analogous to Example 15. Due to the viscosity-lowering

action of the surfactant, the suspension not adhering to the wall flowed completely out of the channels without problems. Owing to the high solids content of the suspension used, 115 g of active composition per liter of catalyst could be applied in a single coating step. No channels of the honeycomb were blocked with active composition. The layer thickness of active composition was about 60 μm .

10 **Example 17. (Catalyst 2 according to the invention):**

602 g of TiO_2 (BET about 30 m^2/g) having a mean particle diameter of 0.1 μm , 220 g of V_2O_5 and 120 g of calcium dodecylbenzenesulfonate were suspended in 885 ml of deionized water and stirred for 18 hours to achieve homogeneous dispersion. The solids content of the suspension obtained was 50% by weight. 60 g of organic binder, namely a copolymer of vinyl acetate and vinyl laurate, in the form of a 50% strength by weight aqueous dispersion were then added. Using this coating suspension, a monolithic ceramic support honeycomb made of cordierite and having a cell density of 200 cpsi and dimensions of 7.5 cm \times 7.5 cm \times 15 cm was coated using a method analogous to Example 15. Due to the viscosity-lowering action of the surfactant, the suspension not adhering to the wall flowed completely out of the channels without problems. Owing to the high solids content of the suspension used, 108 g of active composition per liter of catalyst could be applied in a single coating step. No channels of the honeycomb were blocked with active composition.

Example 18 (Catalyst 3 according to the invention):

To produce a catalyst based on a TiO_2 having a larger mean particle diameter, 785 g of TiO_2 (BET about 30 m^2/g) having a mean particle diameter of 0.4 μm , 196 g of V_2O_5 and 46 g of alkyl(C_8 - C_{10})polyoxyethylene ether phosphate were suspended in 910 ml of deionized water and stirred for 18 hours to achieve homogeneous

dispersion. The solids content of the suspension obtained was 52% by weight. 60 g of organic binder, namely a copolymer of vinyl acetate and vinyl laurate, in the form of a 50% strength by weight aqueous dispersion were then added. Using this coating suspension, a monolithic ceramic support honeycomb made of cordierite and having a cell density of 200 cpsi and dimensions of 7.5 cm x 7.5 cm x 15 cm was coated using a method analogous to Example 15. Due to the viscosity-lowering action of the surfactant, the suspension not adhering to the wall flowed completely out of the channels without problems. Owing to the high solids content of the suspension used, 97 g of active composition per liter of catalyst could be applied in a single coating step. No channels of the honeycomb were blocked with active composition.

Example 19 (Oxidation of o-xylene/air mixtures having a low o-xylene concentration):

To examine the catalytic properties, the catalysts were tested for suitability in (by way of example) the oxidation of o-xylene and compared to a conventional catalyst produced according to the prior art (ring-shaped catalysts). The test apparatus used comprised an adiabatic, i.e. uncooled, insulated reactor. The reactor was constructed so that it could be charged both with catalyst rings and with a honeycomb catalyst according to the invention. An air preheater by means of which the o-xylene/air mixture could be heated to 300-360°C was installed upstream of the reactor. The cross-sectional inflow area of the catalyst was 19.6 cm² and the catalyst fill height was 10.2 cm. The experiments were carried out at a space velocity of 20,000 h⁻¹. The concentration of o-xylene in the gas mixture at the reactor inlet was in the range from 500 to 600 mg/standard m³. The o-xylene concentration was measured by means of gas chromatography and also an on-line FID detector. The

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reaction gas leaving the reactor was collected in acetone and the constituents were determined quantitatively by means of gas chromatography. The content of carbon monoxide and carbon dioxide in the outlet gas from the reactor was determined directly by means of infrared measurement.

The catalysts from Comparative Example 13 and from Example 16, and also a ring-shaped catalyst (Example 15) as further comparison, were tested using the above-described apparatus. The active compositions of all three catalysts had the same chemical composition.

The test results are summarized in Table 1 below.

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Table 1: Catalyst tests using low-concentration o-xylene/air mixtures

	Comparative catalyst on rings (Example 15)	Honeycomb catalyst with 20 g of active composition/l of catalyst (Example 13)	Honeycomb catalyst according to the invention with 112 g of active composition/l of catalyst (Example 16)
Temperature at gas inlet	340°C	340°C	340°C
o-xylene conversion /mol%	56	82	95
PA selectivity/mol%	41	62	67
O-tolualdehyde/mg/Standard m ³	22	42	12
Phthalide mg/Standard m ³	20	36	14

Example 20 (Suitability of the monolithic catalysts produced according to the invention for (by way of example) the after-reaction of PA process gas from o-xylene oxidation in a post-reactor):

The test apparatus used (post-reactor) comprised an adiabatically operated (well insulated) reaction tube in which the monolithic catalyst of the invention from Example 18 was installed. The post-reactor was installed downstream of a customary PA pilot reactor (main reactor). The gas line between main reactor and post-reactor could be thermostatted so that variable gas inlet temperatures into the post-reactor were possible. Gas sampling points were installed before the inlet and at the outlet of the post-reactor. Furthermore, the reaction gas could be cooled in a condenser (desublimator) either after leaving the main reactor or after leaving the post-reactor and the PA

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formed could be deposited or isolated. The main PA reactor was 3.3 m long and had a tube diameter of 25 mm. The temperature of the reactor was regulated using a circulated salt bath (eutectic melt of potassium nitrate and sodium nitrite). The amount of air fed in was always 4 standard m³/h. The main PA reactor was charged with a commercial PA catalyst and the catalyst fill height was 2.8 m. The salt bath temperatures were selected so that the gas mixture leaving the reactor still had comparatively high contents of unreacted o-xylene and underoxidation products such as phthalide and tolualdehyde. The o-xylene loading upstream of the reactor was constant at 70 g/Standard m³ of gas during the experiments. The air/o-xylene mixture was preheated to 180°C before entering the main reactor.

The reaction gas leaving the main reactor was brought to the desired temperature by means of thermostating and passed through the post-reactor containing the monolithic catalyst. The amount of monolithic catalyst was selected so that a space velocity of 20,000 h⁻¹ resulted.

The reaction gas leaving the post-reactor was subsequently passed through a desublimator in order to deposit the reaction products PA, phthalide, etc.

In order to be able to assess the efficiency of the post-reactor in respect of degradation or further oxidation of the by-products, part of the PA reaction gas both before and after the post-reactor was analyzed by scrubbing the gas in acetone and subsequently determining the o-xylene, phthalide and tolualdehyde contents by gas chromatography. The CO and CO₂ contents in the reaction gas before and after the post-reactor were measured by IR spectroscopy. The PA yield was, as already mentioned, determined by means of deposition in a desublimator or calculated via a mass balance.

The results of the experiments are shown in Table 2 below.

Table 2: Results of the oxidation experiments on PA reaction gas

	Contents* before/without post-reactor	Contents* in % by weight after post-reactor with catalyst from Ex. 18 at various gas inlet temperatures			
		360°C	340°C	320°C	300°C
Phthalide	0.48% by weight	0.005	0.014	0.041	0.101
o-Xylene	0.25% by weight	0	0.004	0.022	0.081
p-Benzoquinone	0.04% by weight	0.012	0.015	0.019	0.022
o-Tolualdehyde	0.21% by weight	0	0.004	0.011	0.026
PA yield	111.0% by weight	111.3	111.5	111.8	112.2

* Based on the total organic constituents in the reaction gas.

The results in Table 2 show that a major part of the underoxidation products can be removed from the reaction gas and oxidized further to PA by using the monolithic catalysts of the invention in a downstream adiabatic reactor (post-reactor) in the PA process. Surprisingly, this also takes place at relatively high space velocities. To achieve the best yield, the after-reaction is advantageously carried out at low gas inlet temperatures. The optimum reaction conditions are a compromise between yield and amount of by-products.

Example 21: (Suitability of the monolithic catalysts produced according to the invention for (by way of example) the after-reaction of PA process gas from naphthalene oxidation in a post-reactor):

The experiment was carried out using a method analogous to Example 20, except that the main reactor was charged with a commercial PA catalyst suitable for naphthalene oxidation and was supplied with a naphthalene/air mixture. The monolithic catalyst of the invention from Example 18 was installed in the post-reactor. In this example too, the salt bath temperature

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in the main reactor was selected so that the gas mixture leaving the reactor still had comparatively high contents of unreacted naphthalene and the by-product naphthoquinone. The naphthalene loading of the feed to the main reactor was a constant 70 g/Standard m³ at 4 standard m³ of gas/h during the experiment.

The results of the experiment are shown in Table 3 below.

Table 3: Results of the oxidation experiments on PA reaction gas from naphthalene oxidation

	Contents* before/without post-reactor	Contents* after post- reactor with catalyst from Ex. 18 at a gas inlet temperature of 350°C
Naphthalene	0.12% by weight	0.02% by weight
Naphthoquinone	0.54% by weight	0.06% by weight
PA yield	99.7% by weight	100.3% by weight

* Based on the total organic constituents in the reaction gas.

The results in Table 3 show that, in the PA process using naphthalene as feed, a major part of the residual naphthalene and the by-product naphthoquinone can be removed from the reaction gas and oxidized further to PA by using the monolithic catalysts of the invention in a downstream adiabatic reactor (post-reactor).